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Report No. 03-67-53

AD819272

THIRD INTERIM ENGINEERING REPORT  
for  
DEVELOPMENT AND FABRICATION OF  
SOLID-STATE HIGH-SPEED OPTICAL DETECTORS

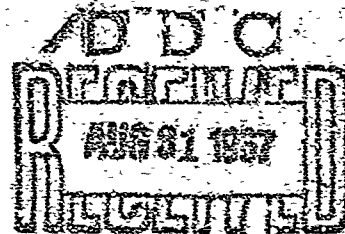
This Report Covers the Period  
16 February 1967 to 15 May 1967

Texas Instruments Incorporated  
13500 North Central Expressway  
Dallas, Texas 75222

Navy Department  
Bureau of Ships  
Electronics Division

Contract No. N00019-67-0001  
Project No. SF021-02-01  
Task No. 9349

June 1967



Report No. 93-67-53

THIRD INTERIM ENGINEERING REPORT  
for  
DEVELOPMENT AND FABRICATION OF  
SOLID-STATE HIGH-SPEED OPTICAL DETECTORS

This Report Covers the Period  
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13590 North Central Expressway  
Dallas, Texas 75222

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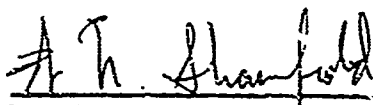
ABSTRACT

Work continued on development and fabrication of a high-speed silicon avalanche photodetector optimized for operation at  $0.9\ \mu\text{m}$ . During this quarter work was concentrated on the fabrication and characterization of diodes.

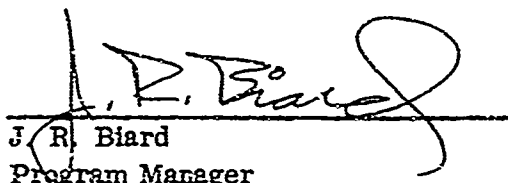
A run of NP $\pi$ P diodes was completed with avalanche breakdown taking place in the active region instead of the edge. However, there were microplasmas, and the gains were low.

A new run of the graded-guardring structure was completed, and the yield was high. With this run and the run processed earlier there are sufficient diodes to meet the contract requirements.

Twenty state-of-the-art samples were characterized and delivered. Results on the N<sup>+</sup>P graded-guardring diodes were very encouraging. Avalanche gains of over 300 were typical. Several of the diodes exhibited theoretical noise characteristics with gains greater than 600. The series resistance was determined to be approximately 25 ohms from forward bias dc measurements. Capacitance of both types of structures was approximately 1.4 pF at breakdown.



W. N. Shaunfield  
Project Engineer



J. R. Biard  
Program Manager

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SECTION I  
TECHNICAL REVIEW

A. PURPOSE

Texas Instruments is conducting a program of development aimed at fabricating photodiodes which satisfy the following goals:

- 1) An NP $\pi$ P photodetector will be developed which utilizes the avalanche mechanism.
- 2) The detector will be optimized to operate at 0.9- $\mu$ m wavelength.
- 3) Design goals for the detector will be a response of 0.15 ns with a sensitivity equal to or better than that of a photomultiplier tube used at the same wavelength.
- 4) The photodiodes will operate at and above room temperature and will not be affected by 100° C storage temperature.
- 5) The photodiodes will be capable of providing amplification of 100 or greater.

The program consists of two phases: I, design and fabrication of the avalanche photodiodes; II, testing and characterization. Phase II will begin with completion of the first diffusion runs to determine whether any modifications in the original design are necessary to achieve the desired characteristics. Specific steps of the program are:

- 1) Obtain photomasks
- 2) Determine optimum diffusions
- 3) Produce experimental epitaxial slices
- 4) Fabricate experimental planar epitaxial diodes
- 5) Characterization of experimental diodes, including quantum efficiency, gain characterization, noise performance, and frequency response.

B. GENERAL FACTUAL DATA

Personnel and Hours Worked

| <u>Professional</u> | <u>Hours</u> |
|---------------------|--------------|
| W. N. Shamfield     | 279.0        |
| Jim Lewis           | <u>21.0</u>  |
| Total Professional  | 300.0        |

| <u>Technician</u> |             |
|-------------------|-------------|
| Jerry Reid        | 302.9       |
| Pauline Harris    | 55.0        |
| Jean Athey        | 55.0        |
| Sam Angelo        | 41.0        |
| Helen Bryant      | <u>16.0</u> |
| Total Technician  | 469.9       |

C. DETAILED FACTUAL DATA

1. Device Design and Fabrication

a. NP $\pi$ P Structure

In the second quarterly report the problem of edge breakdown in the NP $\pi$ P structure, and several possible solutions, were discussed. The first of these solutions was to increase further the P-diffusion concentration. It was pointed out that because of the edge effects the P-diffusion concentration would be even more critical than originally expected. One run of the NP $\pi$ P structure with an increased P-diffusion concentration was fabricated during the third quarter. For the first time in the NP $\pi$ P structure with the wide epitaxial layer, breakdown in the active region of the diode was

observed. Many areas of the slices still had edge breakdown. Of the diodes which showed breakdown in the active area none had a uniform breakdown; large numbers of microplasmas were present. Either the starting material had imperfections or they were introduced during the diffusion steps.

The technique of etching a moat around the diode, so that the material containing the high electric fields at the edge would be removed, was also investigated. The experiment was unsuccessful, the moat ring on the photomask being too small for accurate exposure of the thick KMER required for etching of silicon. Since a completely planar process is more desirable than a mesa process, it was felt that a new photomask to perform the moat-etching experiment was not justified.

Edge breakdown is the result of peaking of the electric field due to the sharp radius of curvature of the junction. It becomes predominant when the junction depth is small compared to the depletion layer width, as in the wide-epitaxial-layer NPT P structure. This effect could be reduced if the junction were made deeper, resulting in a larger radius of curvature of the junction. Several slices from runs processed earlier were rediffused to make the N-type diffusion deeper, causing the diodes to have active region breakdown.

The rediffused diodes still had edge breakdown, and an examination of their capacitance-voltage characteristics revealed the cause. The NPT P structure is characterized by a high capacitance which decreases rapidly with increasing voltage as the depletion region extends through the high-concentration P-diffusion and then through the low concentration  $n$ -layer. A typical capacitance-voltage characteristic is shown in Figure 1 for diode I-1 from run BAPD-3. In the rediffused diode, II-1 from the same run, there is a gradual decrease in capacitance, with increasing voltage indicating that the rediffusion step caused the N-diffusion to move through the P-diffusion region. Bevel lapping and staining of the diodes showed that the N-diffusion moved from approximately  $1.0 \mu\text{m}$  to  $1.5 \mu\text{m}$  during rediffusion. Without the effect of the P-diffusion the diode is an

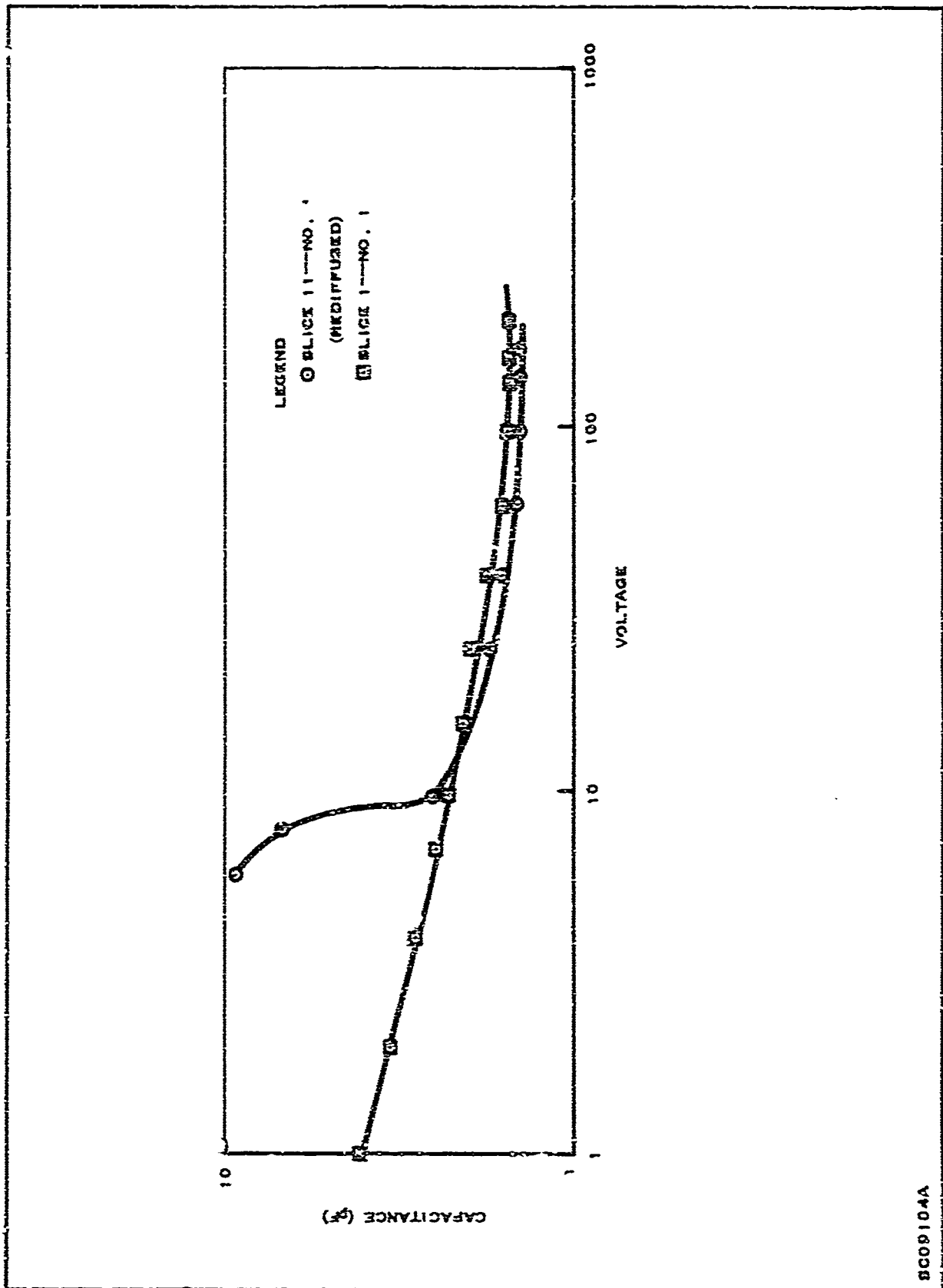


Figure 1. Capacitance versus Voltage for K-11 BAPD-3

N<sup>+</sup>P diode and would break down on the edge. It was hoped that the P-diffusion would move almost as fast as the N-diffusion, the result being an NP<sup>+</sup>P diode with a larger radius on the N-diffusion.

Because of the problems inherent in the wide-epitaxial-layer NP<sup>+</sup>P structure the effort has been discontinued. No new epitaxial slices were ordered during the third quarter. The remaining time will be spent on the N<sup>+</sup>P structure with the graded guarding.

b. N<sup>+</sup>P Structure

In the second quarterly report the preliminary results of the first run of the N<sup>+</sup>P structure were discussed. The yield was very good and the diodes had high uniform gain. Bevel lapping and staining of the diodes showed the graded guarding junction to be 4-5  $\mu$ m deep, and the active region to be 1.0  $\mu$ m deep. During the third quarter an additional run of the N<sup>+</sup>P structure was fabricated, with results similar to those of the first run. With these two runs there are sufficient diodes to meet the contract requirements.

Because of the low impurity concentration in the substrate of the N<sup>+</sup>P structure, the series resistance is higher than that in the NP<sup>+</sup>P structure. This can be reduced by fabricating the diode in an epitaxial layer on a high-concentration substrate. During the third quarter one run of the N<sup>+</sup>P structure was fabricated on epitaxial slices normally used for the NP<sup>+</sup>P structure. Since the epitaxial-layer impurity concentration was too low, the guarding diffusion went too deep and the depletion region punched through the epitaxial layer. As a result the electric field was higher at the edge, and the diodes had edge breakdown. The epitaxial-layer thickness should be so chosen that the combined depth of the diffusion and the width of the depletion region at breakdown are greater than the epitaxial-layer width. New epitaxial material satisfying these requirements has been ordered and the epitaxial N<sup>+</sup>P structure, an N<sup>+</sup>PP<sup>+</sup> structure, will be

fabricated. These new fabrication and material charges are being funded by the company; however, if the effort is successful before the contract is over, this type of diode will be supplied on the contract.

c. Package and Diode Mount

The diodes supplied on the contract are being fabricated in the coaxial pill package shown in Figure 2. Not shown is the lid, which has a lens formed in a 40-mil aperture. Using a collimated light source, such as a laser, the lens projects a spot on the diode less than 10 mils in diameter. The package can be mounted in a PC board or in a BNC connector using the diode mount shown in Figure 3. With the diode and pin installed, the shell is slid inside the BNC connector, making sure the shell contacts the top ring of the diode. In the normal reverse biased mode for the  $N^+P$  structure the pin is biased negative with respect to the shell.

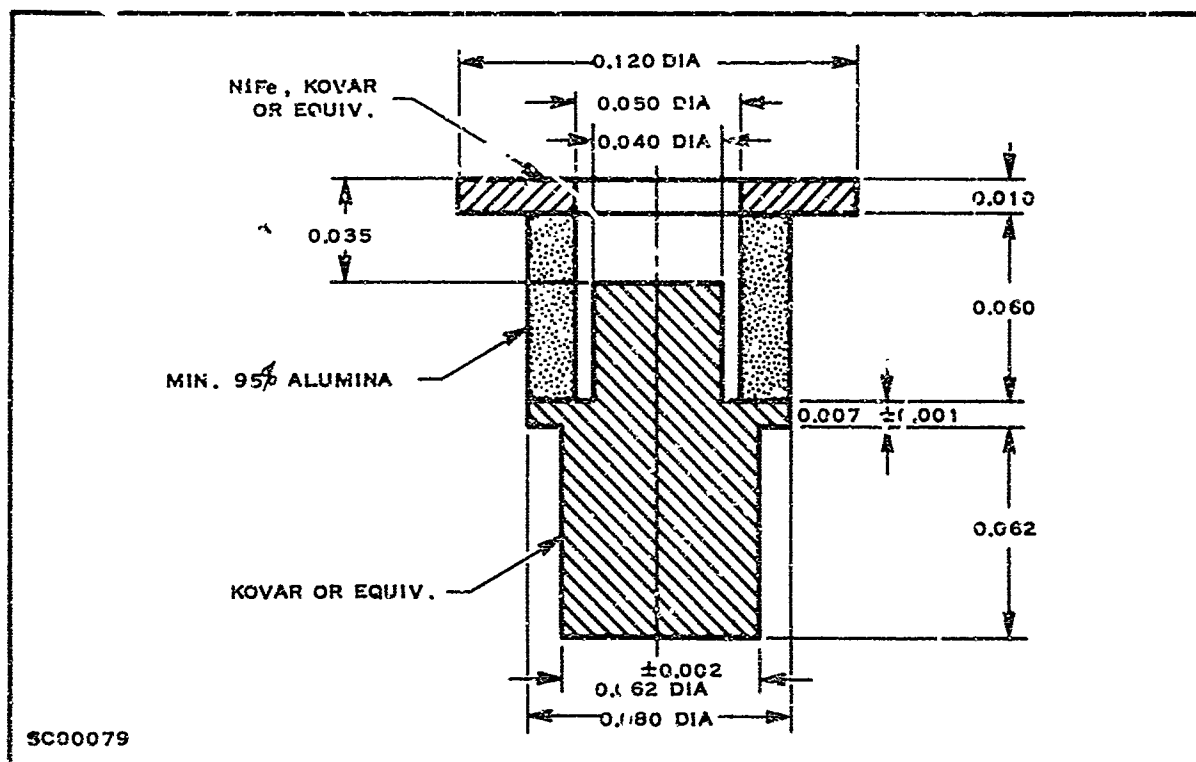


Figure 2. Coaxial Pill Package

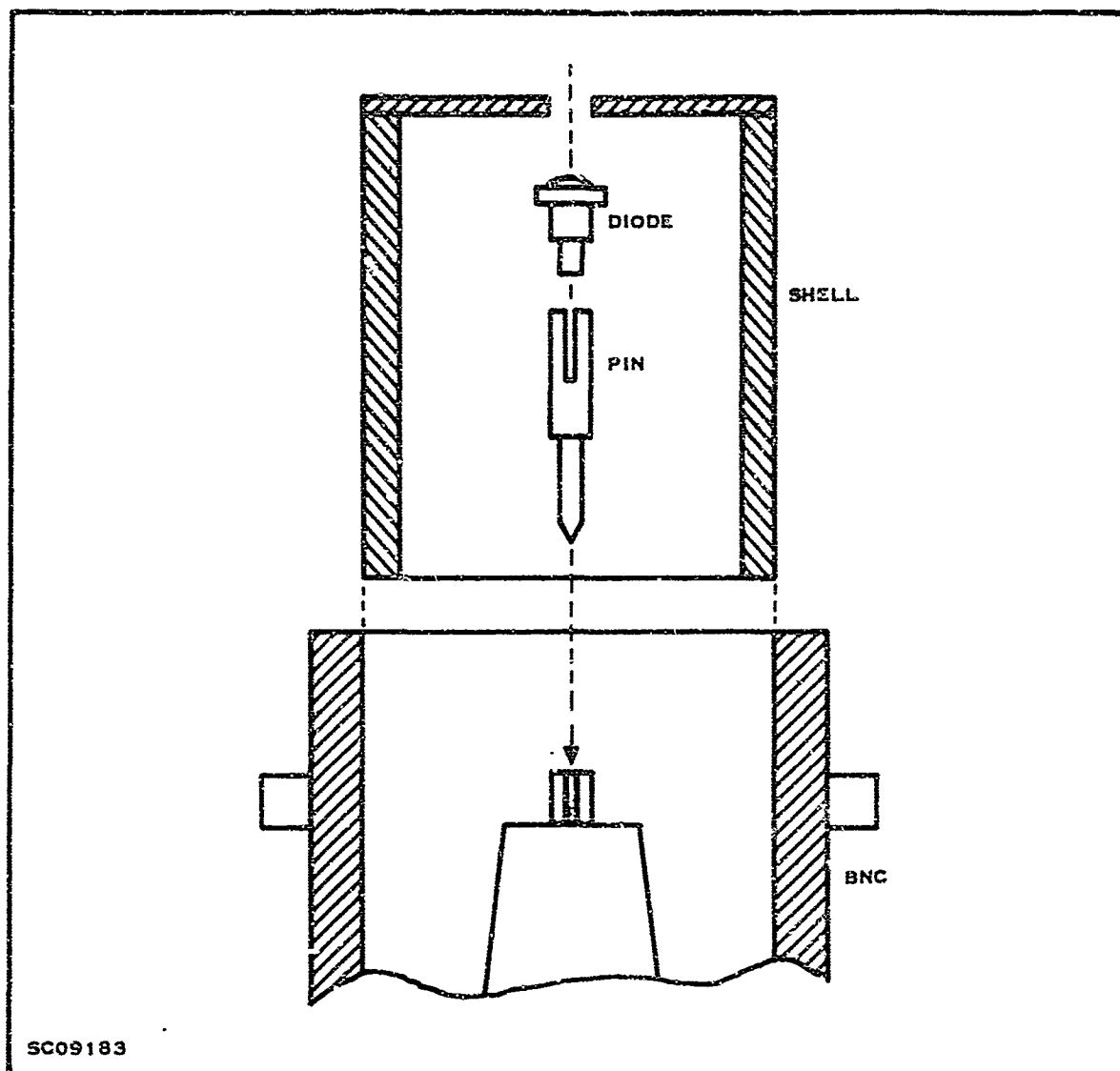


Figure 3. BNC Diode Mount

## 2. Device Characterization

The following paragraphs describe results obtained from the characterization of 20 state-of-the-art avalanche photodiodes delivered during the third quarter. This group consisted of 10 diodes of the  $NP\pi P$  structure, runs Nos. BAPD-3 and BAPD-7; and 10 diodes of the  $N^+P$  graded-guardring structure, run No. BSAPD-1. A summary of the results obtained is presented in the accompanying table. The 10  $NP\pi P$  diodes, although having low gain, represent state-of-the-art devices of the wide epitaxial  $NP\pi P$

Table: Characteristics of BuShip Avalanche Photodiodes

| Run No.   | Device No. | Breakdown Voltage Volts | Gain M | Noise Slope d | Bulk Leakage Current nA | Remarks     |
|-----------|------------|-------------------------|--------|---------------|-------------------------|-------------|
| BSAPD-I   | 1          | 167.71                  | > 400  | 2.25          | —                       | Low gain    |
|           | 2          | 171.93                  | > 300  | 2.4           | —                       |             |
|           | 3          | 167.23                  | ~ 20   | —             | —                       |             |
|           | 4          | 173.66                  | > 640  | 2.24          | 0.85                    |             |
|           | 5          | 159.98                  | ~ 200  | 2.27          | —                       |             |
|           | 6          | 170.02                  | > 350  | 2.24          | 0.5                     |             |
|           | 7          | 164.28                  | ~ 280  | 2.24          | 1.2                     |             |
|           | 8          | 156.13                  | ~ 80   | 2.22          | 1.2                     |             |
|           | 9          | 173.49                  | > 350  | 2.23          | 0.5                     |             |
|           | 10         | 176.59                  | > 710  | 2.25          | 1.5                     |             |
| BAPD-3I   | 2          | 181.35                  | —      | —             | }                       | Low gain ~2 |
|           | 3          | 208.85                  | —      | —             |                         |             |
|           | 4          | 215.43                  | —      | —             |                         |             |
|           | 6          | 215.59                  | 2.5    | —             |                         |             |
| BAPD-3II  | 1          | 208.35                  | 4.0    | —             | }                       | Low gain    |
|           | 3          | 206.01                  | 2.5    | ~ 3           |                         |             |
|           | 5          | 198.69                  | 4.0    | ~ 2.28        |                         |             |
| BAPD-7III | 1          | 274.91                  | 2.0    | —             | }                       | Low gain    |
|           | 2          | 288.72                  | —      | —             |                         |             |
|           | 3          | 268.32                  | —      | —             |                         |             |

structure, and were included since that was the original structure proposed. The  $N^+P$  diodes are much superior in performance and, because of their high gain, allowed a more complete characterization.

a. Capacitance

The capacitance of both types of diodes is approximately 1.4 pF at breakdown. A typical capacitance-voltage characteristic is shown in Figure 1 for the

NP $\pi$ P structure and Figure 4 for the N<sup>+</sup>P structure. The capacitance measurements were made on diodes mounted in the coaxial pill package which has a package capacitance of 0.3 pF. Since the measurements were made at low frequency, 1 MHz, the junction capacitance can be found by subtracting the package capacitance from the measure capacitance. At high frequencies the diode series resistance would complicate the computation.

b. Gain Characteristics

Avalanche gain for the measurements was found by taking the ratio of the diode photocurrent at high reverse bias near breakdown to the photocurrent at a low bias below breakdown. Although the measurements can be made at dc, the test on the diodes was made using a 400-Hz amplitude modulated light source at 9200 Å. Using the photoreponse at 30 volts for a reference gain of one, the typical gain-voltage characteristic for a graded-guardring diode is shown in Figure 5. The gain-voltage characteristic for avalanche has been described by Miller\* as

$$M = \frac{1}{1 - (V/V_B)^n}$$

For the data shown in Figure 5 and  $M > 16$ ,  $n$  in the above equation is 0.42. For lower gains  $n$  becomes larger.

The gain shown in the table is the gain at which the measuring circuit saturated or excess noise occurred, indicating a microplasma went into sustained breakdown.

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\* S. L. Miller, "Ionization Rates for Holes and Electrons in Silicon," Phys. Rev., Vol. 105 (February 1957), pp. 1246-1249.

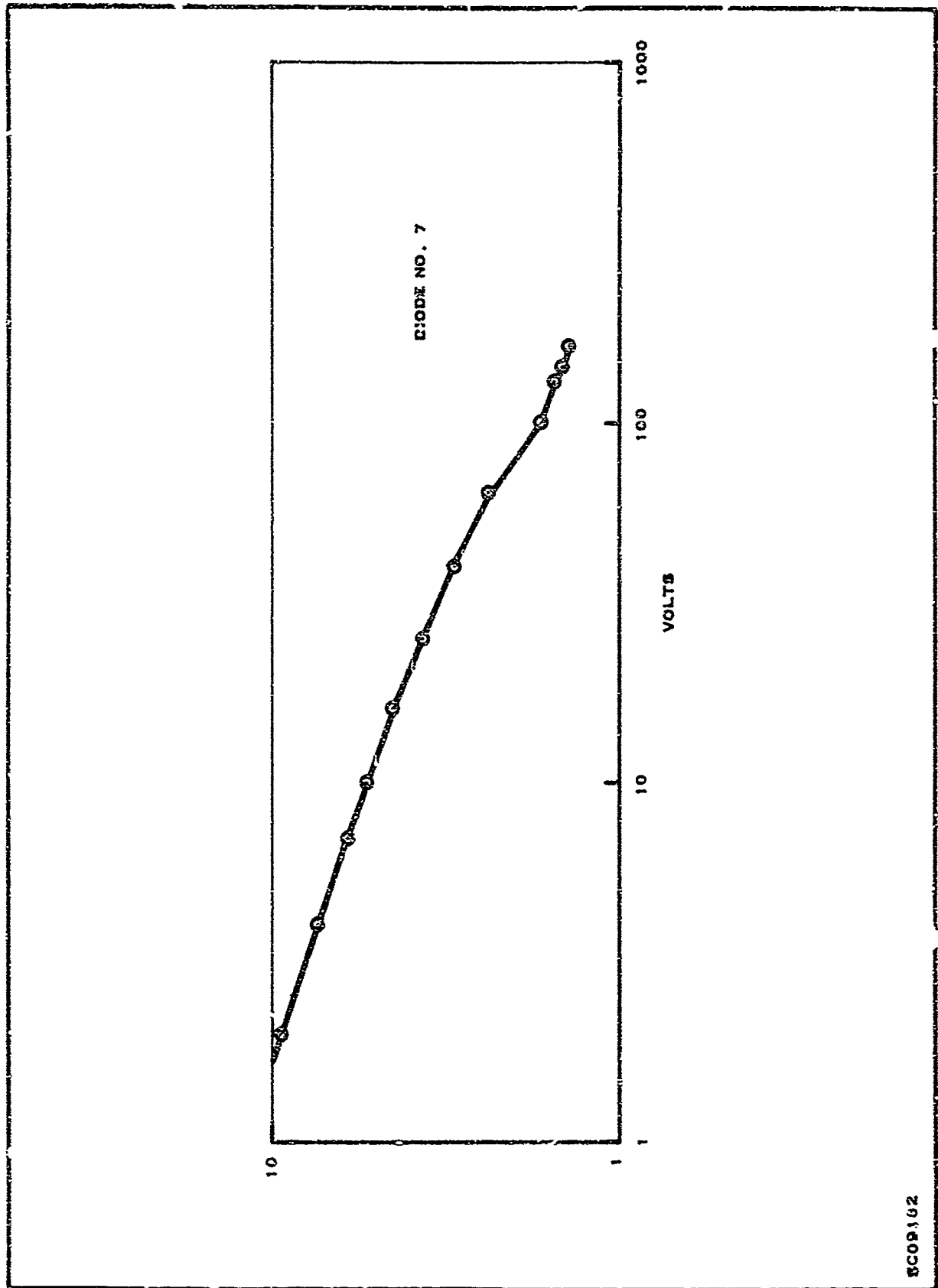


Figure 4. Capacitance versus Voltage for N<sup>+</sup>P Structure (Run BSAPD-1)

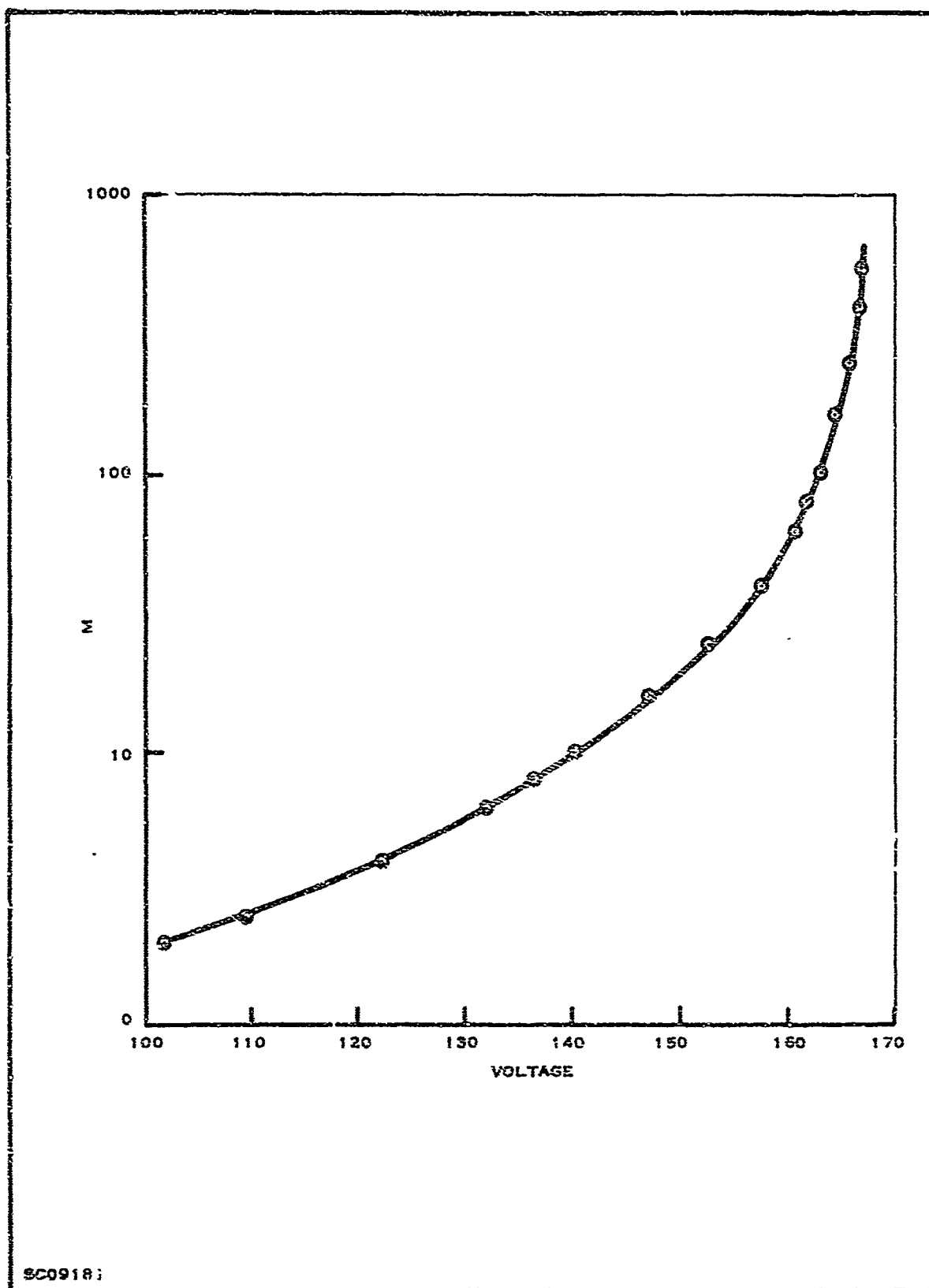


Figure 5. Avalanche Gain versus Bias Voltage for Mode  
BSAPD-I No. 1 at 9200 Å

c. Noise Characteristics

The noise of the avalanche process has been described by McIntyre\* as

$$\overline{i_n^2} = 2 q \Delta f I_\phi M^d$$

where

$\Delta f$  is the bandwidth

$I_\phi$  is the dc photocurrent

$q$  is the electronic charge

$M$  is the gain

$d$  is the noise slope

The noise current squared was measured in a system at a center frequency of 3.8 KHz and a bandwidth of 2.3 KHz. A plot of the typical characteristics is shown in Figure 6. The dc photocurrent was 16.5 nA. The data are in agreement with the above equation over 7 decades of noise. The noise power is found to increase with  $M$  to the 2.25 power. The measuring circuit saturated at  $M = 710$ , and measurements were not taken at higher gains. The value for  $d$  for the other diodes is shown in the table. Diodes BSAPD-I Nos. 3 and 8 showed a sharp rise in noise from the theoretical, indicating that microplasmas were present in the active area.

d. Bulk Leakage Current

Because of the high substrate resistivity (6.5  $\Omega$  cm) of the graded-guardring structure, this structure has a higher bulk leakage current than the NP $\pi$ P

\* R. J. McIntyre, "Multiplication Noise in Uniform Avalanche Diodes," IEEE Trans. on Electron Devices, Vol. ED-13, No. 1 (January 1966), pp.164-168.

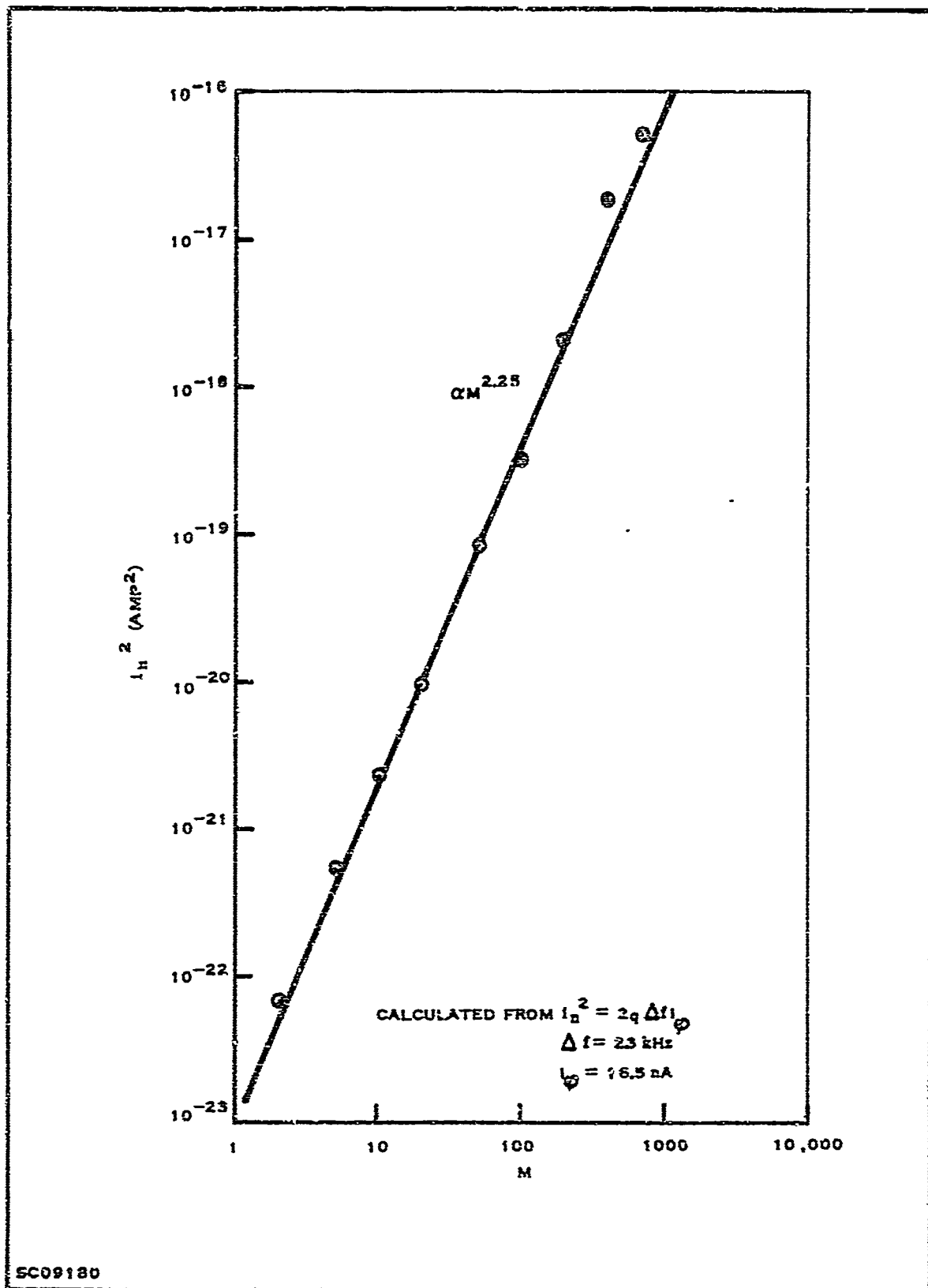


Figure 6. Noise Current Squared versus M (BSAPD-I No. 10)

structure. It is high enough to be measured by plotting the total leakage current versus avalanche gain. Since the surface leakage current is not multiplied, the slope of the curve is the bulk leakage current. The measured bulk leakage, recorded in the table, is typically from 0.5 to 1.5 nA.

#### e. High-Frequency-Gain Characteristics

The avalanche gain was measured at 540 and 1080 MHz and compared with the dc gain. The signal source was an HeNe laser operating at 6328 Å with beat notes at the above frequencies. Reverse bias was supplied through a dc bias tee; the signal was fed directly to a Tektronix Type 661 sampling scope and an HP Type 3406A sampling voltmeter. The dc gain was measured by taking the ratio of the dc photocurrent at the bias voltage and 30 volts. Multiplied photocurrent,  $M_{dc} I_{\phi}$ , was held constant at 1.0 mA to allow the signal to be seen at low gain while avoiding current saturation effects present at high gains. To avoid the high capacitance effects present at low-bias voltages, the  $M_{ac} = 10$  as a reference the ac gain at higher gains was determined. A typical curve of ac gain vs dc gain is shown in Figure 7. The above assumption is shown to be valid since the ac and dc gain is equal out to a gain of 40. Saturation of the ac gain indicates that the diodes have a gain-bandwidth product of approximately 80 GHz.

#### f. Equivalent Circuit

The avalanche photodiode can be represented by the equivalent circuit shown in Figure 8. The signal current,  $i_s$ , is  $m M I_{\phi} \sin \omega t$  where  $m$  is the modulation index. The noise, represented by  $i_n^2$ , was given earlier. Junction capacitance,  $C_j$ , is equal to the measured capacitance minus the package capacitance  $C_p$ , 0.3 pF for the pill package. The series resistance,  $R_s$ , is typically one ohm for the NPP structure. The series resistance for the BSAPD-1 run was determined to be approximately 25 ohms from forward bias dc measurements.

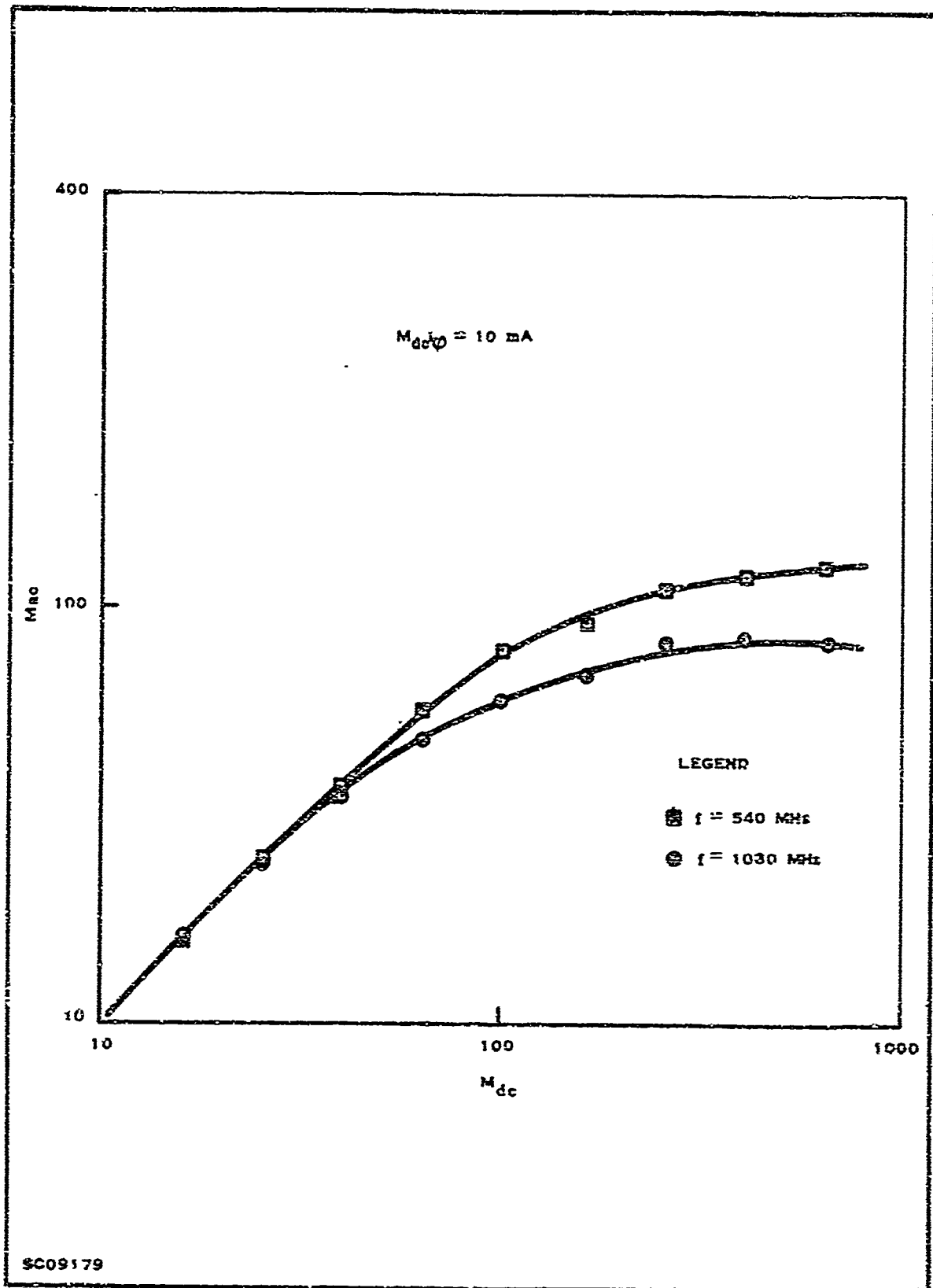


Figure 7.  $M_{ac}$  versus  $M_{dc}$  (BSAPD-I No. 1)

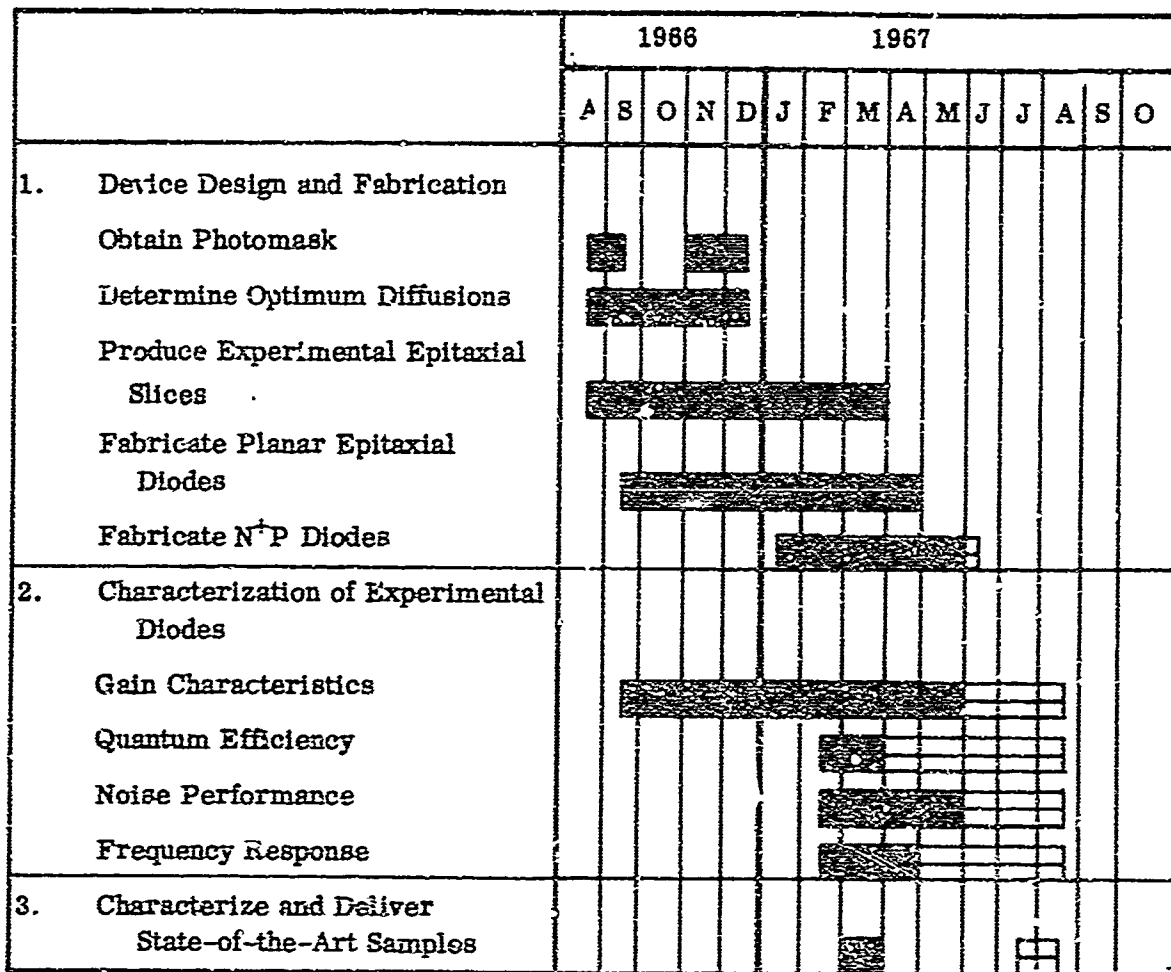
3. Project Performance and Schedule

Texas Instruments Incorporated

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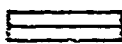


SC079-88A

Legend:



Work Performed



Schedule of Projected Operation

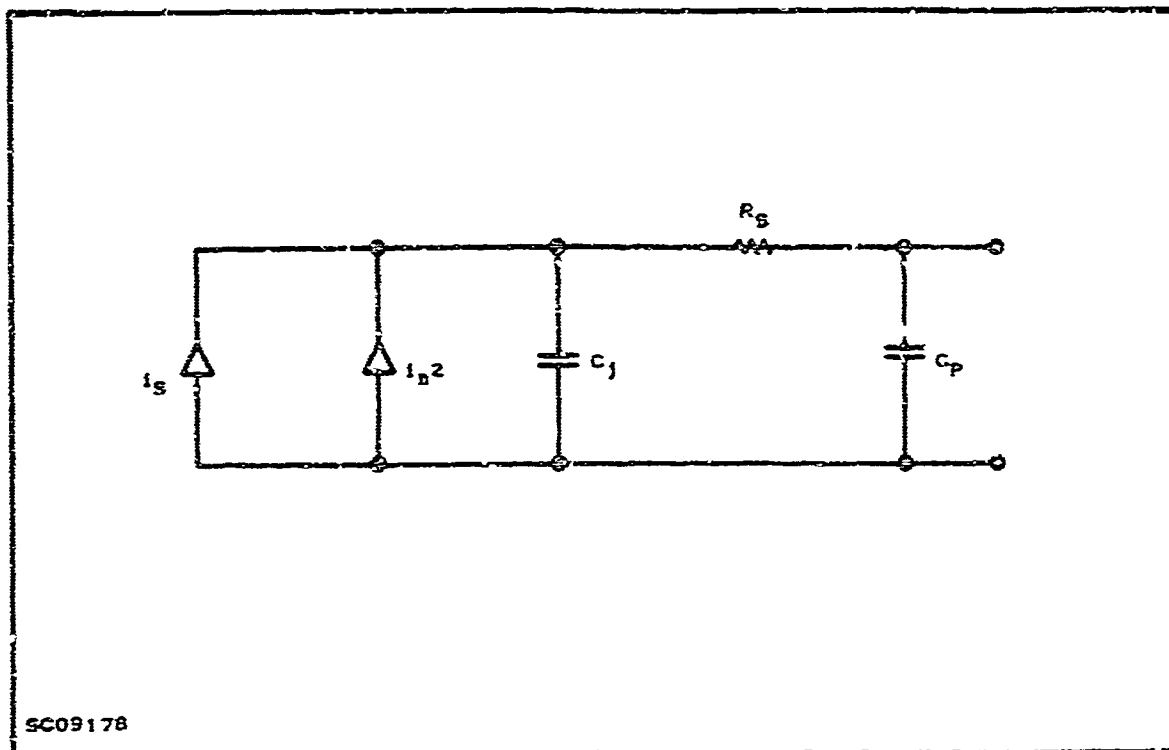


Figure 8. Avalanche Photodiode Equivalent Circuit

Item: Estimated completion in percent of total effort expected to be expended  
(not chronological).

|     |                                       |      |
|-----|---------------------------------------|------|
| 1)  | Obtain Photomasks                     | 100% |
| 2)  | Determine Optimum Diffusions          | 100% |
| 3)  | Produce Experimental Epitaxial Slices | 100% |
| 4)  | Fabricate Planar Epitaxial Diodes     | 100% |
| 5)  | Fabricate $N^+P$ Diodes               | 75%  |
| 6)  | Determine Gain Characteristics        | 75%  |
| 7)  | Determine Quantum Efficiency          | 20%  |
| 8)  | Determine Noise Characteristics       | 60%  |
| 9)  | Determine Frequency Response          | 20%  |
| 10) | Characterize and Deliver Samples      | 50%  |

D. CONCLUSIONS

A run of NP $\pi$ P diodes was fabricated with avalanche breakdown in the active region. However, there were microplasmas and the gains were low.

An additional run of N<sup>+</sup>P diodes was fabricated, and there was a large number of good diodes.

Characterization of the 20 state-of-the-art samples was completed. Several N<sup>+</sup>P diodes exhibited theoretical noise characteristics up to gains of 600. Based on results of the two types of structures, the NP $\pi$ P structure effort is being discontinued in favor of the N<sup>+</sup>P structure.

SECTION II  
PROGRAM FOR NEXT INTERVAL

For the next quarter we plan the following work:

- 1) Mount diodes from runs SSAPD-I and II for final characterization.
- 2) Run complete characterization on final state-of-the-art samples.
- 3) Fabricate and characterize  $N^+PP^+$  diodes if time permits.

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| 13. ABSTRACT  |   |                                    |
| <p>Work continued on development and fabrication of a high-speed silicon avalanche photodetector optimized for operation at 0.9 <math>\mu</math>m. During this quarter work was concentrated on the fabrication and characterization of diodes. A run of N<sup>+</sup>P diodes was completed with avalanche breakdown taking place in the active region instead of the edge. However, there were microplasmas, and the gains were low. A new run of the graded-guardring structure was completed, and the yield was high. With this run and the run processed earlier there are sufficient diodes to meet the contract requirements. Twenty state-of-the-art samples were characterized and delivered. Results on the N<sup>+</sup>P graded-guardring diodes were very encouraging. Avalanche gains of over 300 were typical. Several of the diodes exhibited theoretical noise characteristics with gains greater than 600. The series resistance was determined to be approximately 25 ohms from forward bias dc measurements. Capacitance of both types of structures was approximately 1.4 pF at breakdown.</p> |   |                                    |

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|---|--------|----|--------|----|--------|----|
|   | ROLE   | WT | ROLE   | WT | ROLE   | WT |
| High-speed photodetector<br>Avalanche photodiode<br>Silicon photodetector<br>Low-noise photodiode |        |    |        |    |        |    |

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